An Investigation of Dynamical Processes Influencing Sediment Transport and Morphological Change in Skagit Bay using an Unstructured Grid Coastal Ocean Model

Geoffrey W. Cowles
School for Marine Science and Technology
706. S. Rodney French Blvd.
New Bedford, MA, 02744
phone: (508) 910-6397 fax: (508) 910-6392 email: gcowles@umassd.edu

Award Number: N00014-08-1-1115
http://www.smast.umassd.edu/CMMS/

LONG-TERM GOALS

In this work, we will employ a high-resolution coupled hydrodynamic-sediment model to examine the relative importance of the principal mechanisms controlling the morphodynamics of Skagit Bay. Using the measurements from the extensive observation program supported through the tidal flats DRI, we will examine the capability of a state of the art coastal ocean model, and determine what future extensions may be necessary for continued discovery in this field. Through extensive grid refinement efforts and available high-fidelity bathymetry, a better understanding of the mesh resolution required to resolve the critical processes will be gained. This will guide future application of this class of model.

OBJECTIVES

In this project, we will configure an advanced coupled hydrodynamic-sediment model for simulation of the circulation and sediment transport in Skagit Bay. The model will resolve the range of required scales from the open boundary in Puget Sound (~ 50 km) to the channel networks on the flats (~10-100 m). The coupled model will be validated using available measurements to determine the capabilities and needs of such a system for this class of application. Grid convergence studies will be performed to determine the necessary mesh resolution required to resolve the dominant processes. We will employ the calibrated coupled model to evaluate the relative importance and influence of observed external forcing (fluvial, tidal, wind, wind-wave and surface heating) on sediment dynamics and morphological change of the inter-tidal region of Skagit Bay over a range of time scales from tidal to seasonal.

APPROACH

We will develop and apply a coupled hydrodynamic-sediment model of Skagit Bay. Due to the complexity of the coastline and bathymetry and the large range in dynamical scales in macrotidal estuaries, the unstructured-grid coastal ocean model FVCOM was selected. FVCOM is a Fortran90 software package for the simulation of ocean processes in coastal regions (Chen et al., 2003, 2006). The publicly available model has a growing user base and has been used for a wide variety of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **An Investigation of Dynamical Processes Influencing Sediment Transport and Morphological Change in Skagit Bay using an Unstructured Grid Coastal Ocean Model**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School for Marine Science and Technology,706. S. Rodney French Blvd,New Bedford,MA,02744**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

applications, including work in Skagit Bay (Yang and Khangaonkar, 2008). The kernel of the code computes a solution of the hydrostatic primitive equations on unstructured grids using a finite-volume flux formulation. For the vertical discretization, a generalized terrain-following coordinate is employed. The model is fully parallelized using a Single Program Multiple Data (SPMD) approach (Cowles, 2008). FVCOM will be coupled with the Community Sediment Transport Modeling System (http://woodshole.er.usgs.gov/project-pages/sediment-transport/). The model includes transport of both the suspended load and bedload. The number of sediment classes is flexible, and for each class, parameters such as critical shear stress, mean diameter, and settling velocity must be defined. Complex bed dynamics are included with a user-prescribed number of layers defined by the layer number, fractions of each sediment class, an age, and a thickness. Recently, support for cohesive sediment modeling has been implemented in CSTMS and is currently undergoing testing.

Beginning from the aforementioned FVCOM model of Skagit Bay developed at PNNL, we will work to modify this model to resolve the processes that are the focus of the proposed work. This work includes the initialization and parameterization, calibration of the sediment model, modification of the mesh resolution and expansion of the domain outward from Skagit Bay. The updated model will be validated using measurements obtained through observational programs in the tidal flats DRI.

An open loop mesh adaptation procedure will be used to refine the initial model setup to make sure the mesh has the required grid spacing in tidal channels and flats needed to resolve the processes examined in the proposed work. This will ensure that we have a grid refined solution for our morphodynamic studies to constrain the influence of spatial discretization errors in the model results. To do so, we will generate a series of coarser meshes from the initial grid using the method of Maximal Independent Sets. Solutions for the baseline case will be obtained on the coarser meshes and Richardson extrapolation of the bed thickness change and integrated current energy across the mesh levels will be utilized to determine an estimate of local spatial discretization error. The mesh will be adapted locally by inserting and deleting points based on this heuristic. This process will be repeated until suitable grid convergence is achieved for the given forcing and available bathymetry. Using this method we will take advantage of the variable resolution allowed by the unstructured mesh, and rely on the dynamics to drive the background length scale.

We will force the model using idealized and realistic conditions to examine the contributions of external forcing to the morphodynamics of the tidal-flat. In these process studies the rates of freshwater discharge and fluvial sediment supply will be varied, along with the tidal phase, and the sea level to examine the impact on net sediment transport and circulation in Skagit Bay. In addition, we will examine the impact of resuspension driven by episodic wind and wave events. These studies will be used to examine how the intertidal zone adjusts on event time scales, through the spring-neap cycle, and on seasonal time scales.

WORK COMPLETED

1. Model setup

Following acquisition of the FVCOM Skagit Bay model from PNNL, the model has been been modified to make it suitable for answering the scientific questions of the DRI. This includes an increase in the resolution, modification of the domain, and improvement of the bathymetry. These are outlined in more detail below.

Domain

The model boundaries have been extended into Juan de Fuca strait and through the Saratoga Passage to the south end of Whidbey Island at Sandy Point (Fig 1). The extensions were performed to ensure that the open boundary regions outside Skagit Bay contained had a large enough volume relative to the tidal prism to reduce the influence of the open boundary hydrography and sediment concentration on the interior model solution. The model is forced by tides at three open boundaries: Sandy Pt, Juan de Fuca, and Swinomish.

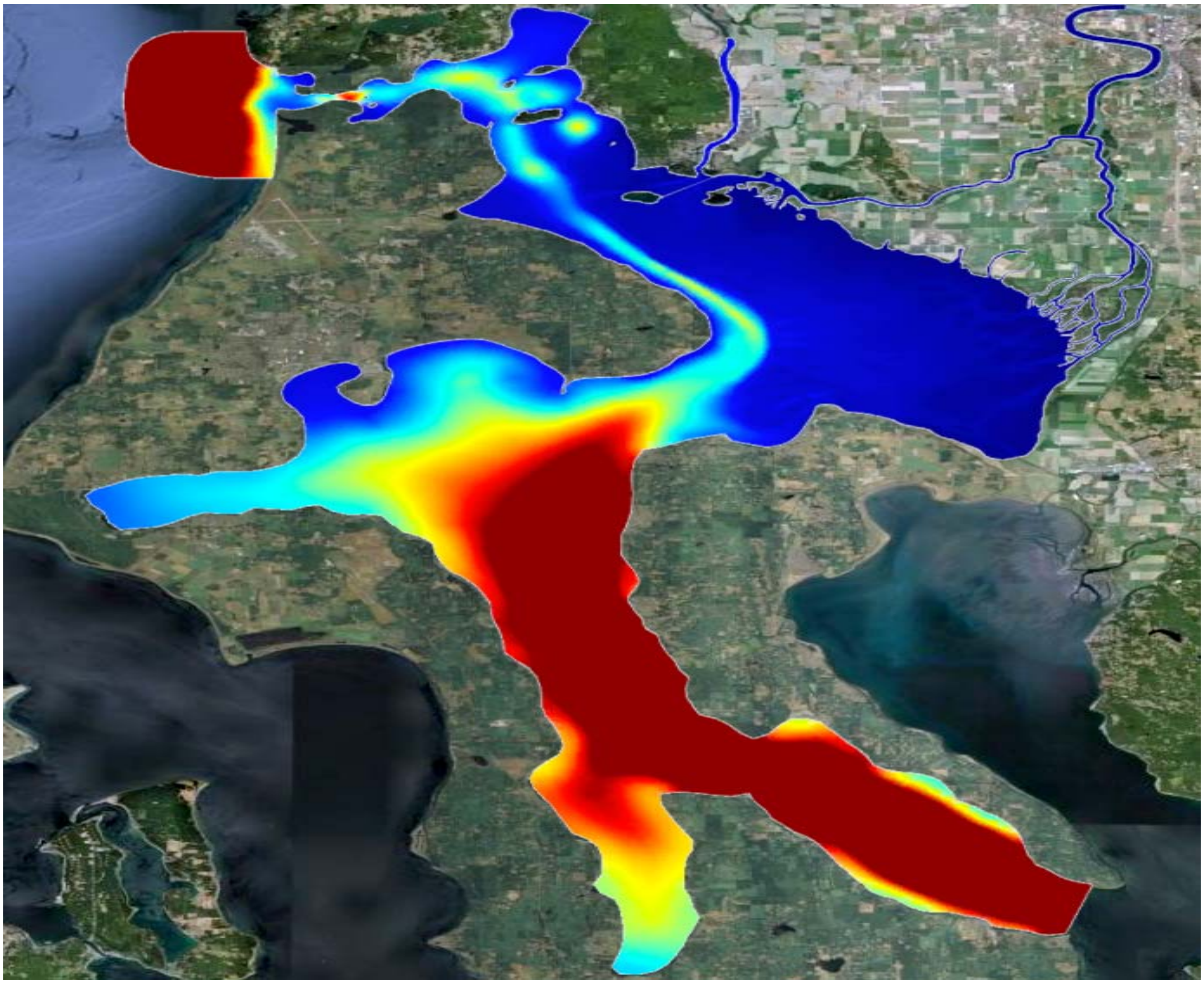

Figure 1: Skagit Domain and Bathymetry (Google Earth overlay)

Bathymetry

The bathymetry consists primarily of two components, the Puget Sound Digital Elevation Map (PSDEM2005) with full coverage of the model domain and the SRSC Fir Island Lidar survey, primarily constrained to the upper flats along Fir Island. This data was projected and reinterpolated into geographic coordinates by Rich Signell (USGS Woods Hole) and is available for download and interrogation through several mechanisms via the USGS Thredds catalog (http://coast-enviro.er.usgs.gov/thredds/bathy_catalog.html, Puget Sound DEM: 2005).

On the South Fork flats, the bathymetry is still influenced by artifacts present in the DEM. Several attempts were made to eliminate these artificts which manifest themselves as lines of discontinuity in the bathymetry in roughly the along-flat direction at intervals of roughly a kilometer. At this time these have principally been dealt with by smoothing in the cross-flat direction to try to maintain a reasonable large-scale cross-flat slope without smoothing channel features. Digital elevation in the primary river beds has been estimated in collaboration with Dave Ralston (WHOI). Channel centerlines for the North Fork, South Fork, and Main Branch of the Skagit River up to Mt. Vernon along with Steamboat and Freshwater Slough were provided to D. Ralston. De-tided depth collected from the WHOI survey (Geyer et al.) is then interpolated on the tracks and applied to model rivers under the assumption of zero cross-river gradients. While this method produced reasonable slopes, some modification at the North/South fork split was necessary to maintain continuity. Deepwater Slough was graded in the same manner, although at this time there is limited flux through the Slough. Bathymetry in the swinomish is modified to enforce the dredged controlling depth of 6.8 feet.

Forcing

The model is forced using freshwater flux from the Mt. Vernon stream gauge and specified sea surface elevation (at present, tidal elevation) at the open boundaries. Additional experiments will use temporally-varying wind, wave-induced bottom stress, and sediment load.

Model Versions

Two series of models have been generated. The 3.xx series models are generated using the mesh generation component of the Surface Modeling System (SMS) software which uses an advancing front technique to generate Delaunay-conforming grids. Working with D. Ralston (WHOI) these models have been continually refined to ensure stability in the integration while maintaining the level of necessary resolution. Currently two versions (3.15, 3.16) are being used by D. Ralston for hindcast simulations of Skagit Bay. A summary of metrics for these models is included below. The 4.xx series of models are generated using the open source meshing software *gmsh* (http://www.geuz.org/gmsh/). This software has the capability of performing automated adaptive mesh refinement. The mesh can be adapted locally by specifying a background length scale to *gmsh*. Version 4.3, a relatively coarse mesh (table 1) has been used for calibrating and validating the tidal dynamics.

Table 1: Specifications of Current Skagit Models

Model	Elements	Layers	Resolution [Flats/Mean]	Time Step (s)	iterations/(core-hour)
skg3.15	188K	21	10m / 37m	0.5	150
skg3.16	112K	21	20m / 50m	1	255
skg4.3	15K	11	100m / 200m	5	7000 (barotropic)

2. Non-Cohesive dynamics from CSTMS implemented into FVCOM

Dynamics for cohesive sediment transport have been added to the sediment model in FVCOM. These have been extracted primarily from the implementation of the Community Sediment Transport Modelling System (CSTMS) currently available in the CSTMS branch of the Regional Ocean Model System (ROMS). The principal modification to the existing FVCOM sediment model was the treatment of the bed. For cohesive substrates, the critical shear stress is a property of the bed which evolves due to consolidation, swelling, and bioturbation.

To test the updated FVCOM sediment model we have developed a wrapper to the module to drive 1-D solutions of sediment in the water column. Time-dependent physical fields (eddy diffusivity, bottom stress, and depth) are generated by the General Ocean Turbulence Model (GOTM) and are used to drive the model. This enables controlled testing of dynamics and sediment algorithms for problems that vary slowly in the horizontal. With C. Sherwood (USGS, Woods Hole) we are in the process of developing a standardized set of 1-D test cases for the purpose of debugging as well as testing the CSTMS model dynamics in FVCOM. This cases will explore steady state forcing as well as tidal (mixed tides) and event-scale. With guidance from C. Sherwood we are also examining several possibilities for inclusion of flocculation dynamics within the CSTMS framework, focusing on methods that account for redistribution of sediment across classes associated with floc breakup and formation (Xu et al., 2008).

RESULTS

1. Tidal Modeling

Considering the depth of water and the relative protection and short fetch of the Bay, the tides represent the dominant external forcing over the broad scale of the flats and thus must be simulated as accurately as possible. However due to the extensive flooding and drying of the flats, the lateral mixing associated with the extreme currents of Deception Pass and the diurnal inequality, achieving high level of tidal model skill is challenging. A coarse model has been used for testing the model's ability to reproduce the tidal harmonics at stations around the Bay. This model runs quickly (Table 1) and thus is useful for tidal calibration. This model can be used to inform the forcing and setup of the high-resolution models which are too large to be practical for anything but production runs. Two key with the tidal forcing are the selection of open boundary forcing at the Juan de Fuca open boundary where there are no available harmonics and the treatment of Deception Pass. Tidal harmonics are compared at 9 stations in the domain: Deception Pass Park, Holly Farms Harbor, GreenBank, Coupeville, Crescent Harbor, Sneeoosh Point, Ala Spit, Corney Bay, and Yokeko Point. For the M_2 amplitude and phase (dominant constituent) the average amplitude error is 3.3 cm and the average phase error is 4.5°. The primary source of model-observation error is the upper Skagit where the model leads the observations in the M_2constituent by approximately 6°. We are continuing work on parameterization of the bottom friction in Deception Pass to improve the tidal response in the upper Skagit. Spatially distribution of model-computed M_2 amplitude (m) and phase (°G) are shown in Figure 2.

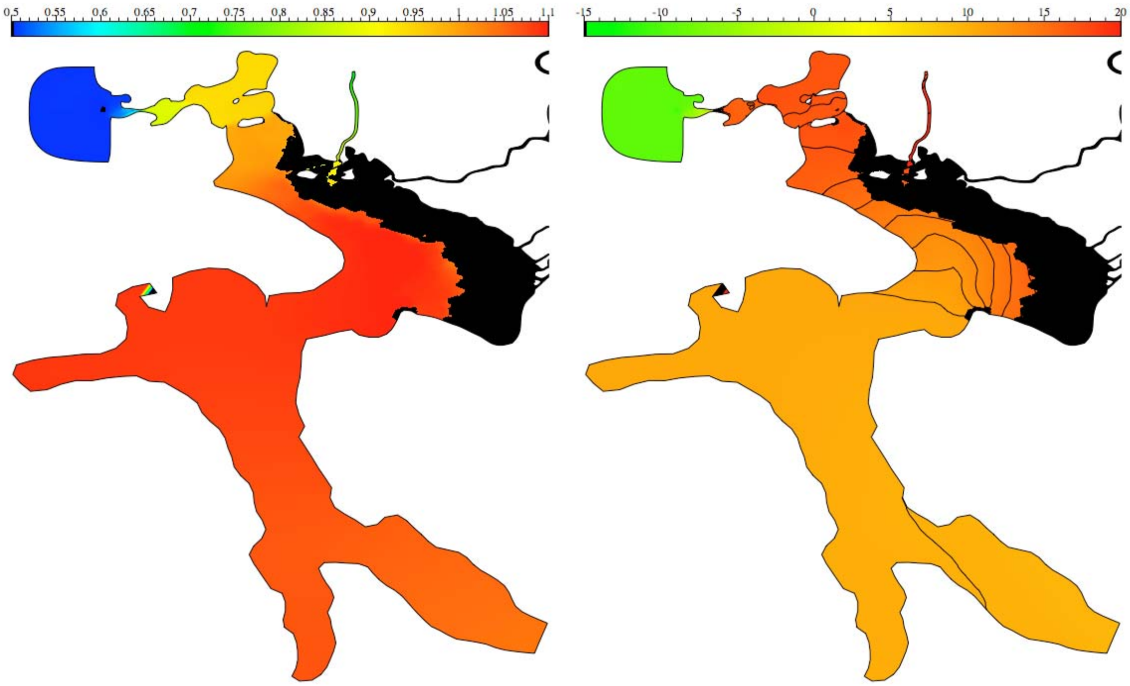

Figure 2: Model-Computed M2 Amplitude (m) [left] and phase (°G) [right] in water greater than 2-m depth

2. FVCOM-CSTMS testing

With guidance from C. Sherwood (USGS), a suite of 1-D test cases for the FVCOM-CSTMS model are being developed. These cases will be used to debug and to test the sediment dynamics module of FVCOM using a range of forcing scenarios. The test cases allow evaluation of parameter sensitivity and comparison with RO.

Table 3: FVCOM-CSTMS 1-D Test Cases

Test Case	Open Channel	Tidal Forcing	Event Forcing	Settling Chamber
Source	Warner et al, 2008	Sherwood et al, 2008 ppt	Sherwood et al, 2008 ppt.	Sherwood et al., 2008 ppt.
Tests	Steady-state equilibrium, turbulence models	Time-varying erosion/deposition, bed composition	Dynamics across two events including bed dynamics	Quiescent settling, steady state bed composition
Physical Forcing	Constant Pressure Gradient	Harmonic Pressure Gradient	Time-varying Surface Stress	None
Sed Classes	Sand	Mud/Mud	Mud/Mud	Mud/Mud

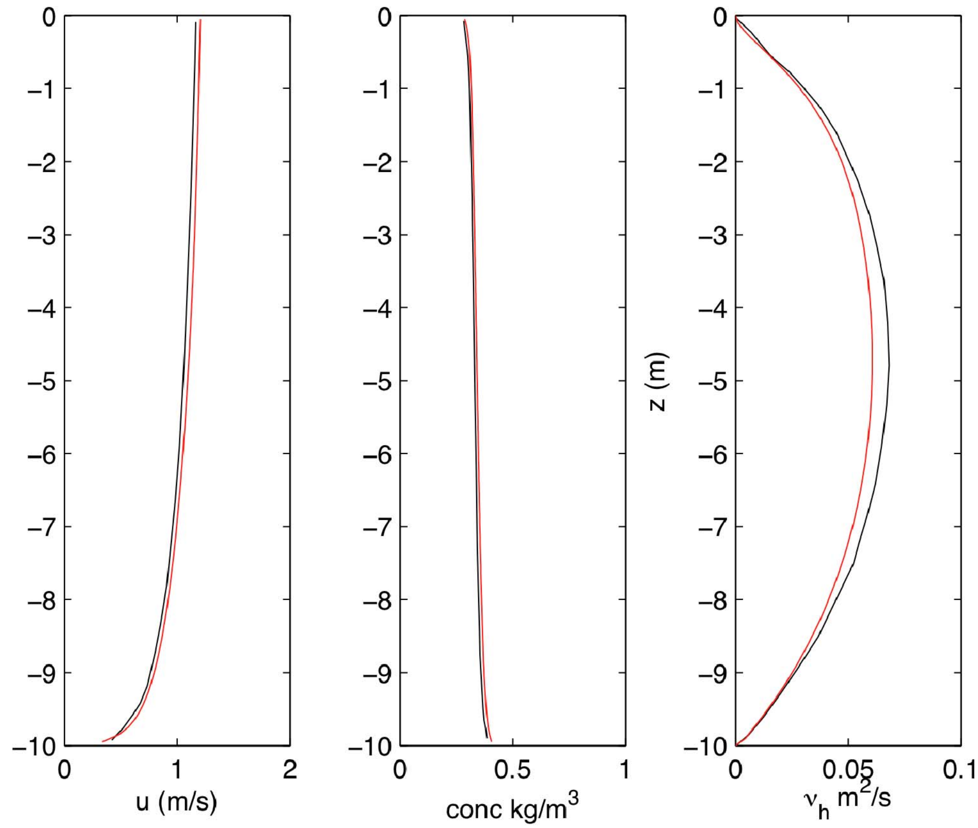

Figure 3: Comparison of FVCOM-CSTMS (red) and ROMS-CSTMS (black) for the open channel sediment test case

IMPACT/APPLICATIONS

A key component of this work is the development of an unstructured grid coupled hydrodynamic-sediment model for the study of tidal flats. The validation efforts will draw on the intensive observation program supported by this DRI and will help to make conclusions about the potential of such a model as well as define future research needs in terms of development or need for additional data. In concert with the scientific findings of other teams, the coupled system will provide a platform by which the influence of external forcing components on tidal flat sediment processes can be isolated and elucidated.

RELATED PROJECTS

In this work we work closely with other investigators participating in the ONR tidal flats DRI. The key collaborators are C. Sherwood and R. Signell (USGS, Woods Hole) who will be assisting with the development, implementation, and validation of CSTMS within FVCOM as well as processing of bathymetry for the model domain. We are also working closely with D. Ralston (WHOI) and J. Lerczak (OSU) in the model development and validation.

REFERENCES

Chen, C, R. C. Beardsley and G. Cowles, (2006). An unstructured grid, finite-volume coastal ocean model (FVCOM) system. Special Issue entitled "Advance in Computational Oceanography", *Oceanography*, **19**(1), 78-89.

Chen, C, R. C. Beardsley and G. Cowles, (2006). An unstructured grid, finite-volume coastal ocean model (FVCOM) system. Special Issue entitled "Advance in Computational Oceanography", *Oceanography*, **19**(1), 78-89.

Cowles, G**.**, 2008, "Parallelization of the FVCOM Coastal Ocean Model", *International Journal of High Performance Computing Applications 22(2) 177-193*.

Sherwood, C., B. Ferré, J.P. Rinehimer, L. Sanford, J. Warner, Cohesive Sediment in CSTMS, *WEBEX presentation*, July 2008.

Warner, J.C., C. R. Sherwood, R.P. Signell, C.K. Harris, H.G. Arango (2008), Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model., *Computers & Geosciences* 34, 1284-1306.

Xu, Fanghua, D.-P. Wang, and N. Riemer, 2008. Modeling flocculation processes of fine-grained particles using a size-resolved method: Comparison with published laboratory experiments, *Continental Shelf Research*, 28, 2668-2677.

Yang, Z, and T.P. Khangaonkar (2008). " Modeling the Hydrodynamics of Puget Sound using a Three-dimensional Unstructured Finite Volume Coastal Ocean Model." In *Estuarine and Coastal Modeling*, ML Spaulding (ed). *Proceedings of the 10th International Conference* (accepted for publication). American Society of Civil Engineers, Newport, RI.